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Room-temperature continuous-wave operation of InAsSb quantum-dot lasers near 2 μm based on (001) InP substrate

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Single-stack InAsSb self-assembled quantum-dot lasers based on (001) InP substrate have been grown by metalorganic vapor-phase epitaxy. The narrow ridge waveguide lasers lased at wavelengths near 2 μm up to 25 °C in continuous-wave operation. At room temperature, a differential quantum efficiency of 13% is obtained and the maximum output optical power reaches 3 mW per facet with a threshold current density of 730 A/cm^2. With increasing temperature the emission wavelength is extremely temperature stable, and a very low wavelength temperature sensitivity of 0.05 nm/°C is measured, which is even lower than that caused by the refractive index change. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1640467]

Semiconductor lasers based on quantum dots (QDs) have attracted considerable effort due to their superior physical properties expected from three-dimensional confinement. While most of the work has been focused on the InAs/GaAs material system at wavelength of 1.3 μm,[1–3] and InP-based InAs QDs to obtain light emitters in the telecom wavelength region (~1.55 μm).[4] Recently, attempts to use InAs nanostructures based on InP substrates to extended the wavelength further into the infrared region of 1.8–2.3 μm are attracting more attention, where lasers are attractive for applications in molecular spectroscopy, remote sensing of atmospheric and planetary gases as well as lidar atmospheric detection and ranging. InAs QDs and quantum-dash lasers have been demonstrated recently at various wavelengths from 1.60 to 2.04 μm.[4–7] Usually large InAs QDs are required for long emission wavelengths; dislocations are sometimes inevitable due to the strain energy relaxation. Therefore, the performance of the InAs QD lasers, especially in the wavelength region of 2 μm, is still limited and room temperature cw operation is not yet realized.

InSb and InAsSb are the smallest band gap binary and ternary in conventional III–V semiconductor material family, and it has been long thought that InSb and InAsSb nanostructures could be used to achieve midinfrared emissions. InAsSb QDs on GaAs were grown to obtain near 1.3 μm emission,[8] photoluminescence (PL) at wavelength of 3.5 μm was reported for InSb QDs in InAs matrix,[9] and InSb QDs of density as high as $4\times10^{10}/\text{cm}^2$ has been achieved by molecular-beam epitaxy.[10] Nevertheless, typical InSb QDs self-assembled using metalorganic vapor-phase epitaxy (MOVPE) have area density of usually less than $5\times10^9/\text{cm}^2$.[9] We have self-assembled high density InAsSb ternary QDs based on InP substrate using MOVPE by creating a local nonequilibrium process and reducing the mobility of In adatoms on the growing surface.[11] Efficient PL in the wavelength range from 1.7 to 2.2 μm has been observed at room temperature.

In this letter, we report lasing characteristics of single-stack InAsSb QD lasers based on InP substrate. The 5 μm ridge waveguide lasers were operated in cw at wavelengths near 2 μm up to temperature of 25 °C. A differential quantum efficiency of 13% is obtained at room temperature, and the maximum output optical power reaches 3 mW per facet with a threshold current density of 730 A/cm^2.

The InAsSb QD lasers were grown on (001) InP substrates using low-pressure MOVPE. Trimethylindium, trimethyantimony, triethylgallium, AsH_3, and PH_3 are used as precursors, and H_2 as carrier gas. Growth temperatures were in the range of 500–550 °C for the InAsSb QD layers, and 625 °C for the rest of structures. Details about InAsSb QDs growth conditions have been described elsewhere.[11] The laser structure consists of a single-stack InAsSb QDs self-assembled in a slightly tensile-strained (less than −0.5% mismatch) InGaAs quantum well with thickness of 7 nm, which is further sandwiched between 150 nm InGaAsP ($\lambda g = 1.35$ μm) and 1.5 μm InP cladding layers on both sides, and finally a 200 nm InGaAs contact layer. Room-temperature PL measurement showed a ground-state peak at 1.98 μm at the edge of a 2 in. wafer with a spectral full width at half maximum of 34 meV, indicating a good homogeneity of the QDs. Based on atomic force microscopy scans on uncapped reference samples, the InAsSb dots have an average lateral size of around 35 and 4 nm in height with an area density of $4\times10^{10}/\text{cm}^2$, as shown in Fig. 1, which indicates that the InAsSb QDs are usually smaller than typical InAs QDs on InP substrate at emission wavelength near 2 μm.[12]

5 μm ridge waveguide lasers were fabricated with cavity lengths between 0.5 and 1.5 mm with both facets left uncoated. The lasers are tested in bar form using a temperature-controlled probe station with an epitaxial-side-up configuration. The thermal impedance is negligible between a laser bar and the copper block, provided large contact area of a laser bar. The optical output power was measured with a thermopile power meter. The emission spectra were obtained by focusing the output optical beam onto the entrance slit of a monochromator.

Ground-state cw lasing has been achieved at room temperature for cavity lengths of 1 and 1.5 mm, with the lasing

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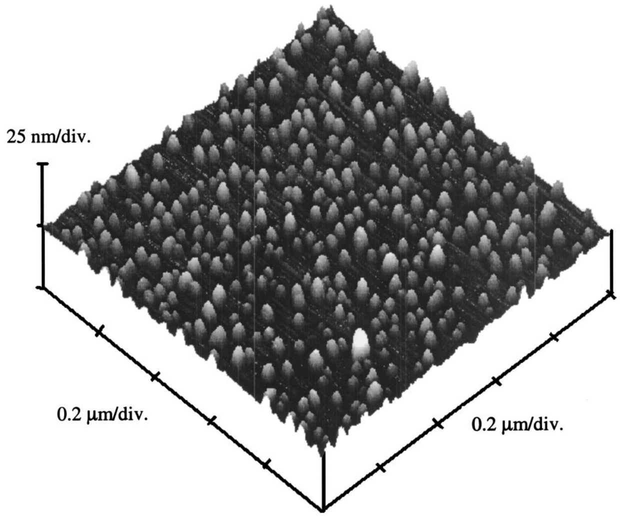

FIG. 1. 1 μm$\times$1 μm atomic force microscopy scans of InAsSb QDs self-assembled on (001) InP.

wavelength between 1.95 and 1.96 μm. Shown in Fig. 2, the room-temperature cw lasing spectra of a 1.5 mm cavity QD laser at different injection current, display some spectral features with three or four broadened longitudinal modes with mode spacing of 2.6 nm. Given an effective refractive index of 3.4, the Fabry–Pérot longitudinal mode spacing should be about 0.37 nm at wavelength of 1.95 μm, there should be 6–7 Fabry–Pérot longitudinal modes within each broadened longitudinal mode,[3,13] which are not visible here due to the resolution of the monochromator. This spectrum characteristic is unique to QD lasers resulting from the presence of noninteracting dots,[14] which is more obvious at lower testing temperatures such as 15 and 10 °C since the homogeneous broadening is smaller at lower temperatures. From the spectra in Fig. 2, the homogeneous and the inhomogeneous broadening are estimated to be 1 and 3–5 meV, respectively, which are small compared with those of InAs QD lasers at 1.3 μm on GaAs substrate[14] and 1.67 μm on InP previously reported.[6] Smaller size dots of InAs QD lasers on GaAs usually have large (in)homogeneous broadenings, while larger size dots of long wavelength lasers on InP usually have smaller (in)homogeneous broadenings. This broadening difference is believed at least partially a result of quantum size effect of different size dots.

Figure 3 shows the single facet light output characteristics versus current of a 1.5 mm cavity length laser operating cw measured at different temperatures. At 10 °C, the threshold current and threshold current density are about 55 mA and 730 A/cm^2, respectively, the single facet output power exceeds 3 mW and the differential slope efficiency is about 13%, which is higher than that of InAs quantum-dash lasers at 2.03 μm[7] but still much lower than that at 1.66 μm.[4] The characteristic temperature T_0 is 35 K at temperatures below 15 °C and 20 K above 20 °C. With increasing temperature, the differential slope efficiency decreases gradually to 11% at 20 °C then drops abruptly to about 3% at 25 °C, suggesting a poor electron confinement as a result of Sb incorporation in the QDs, even though the Sb composition in InAsSb QDs has not been determined.

Another unique property of QD lasers is the very low wavelength temperature sensitivity because of the inhomogeneously broadened transitions of the QD ensemble.[15] Figure 4 plots lasing spectra at different temperature under injection current of 1.6 I_{th}, as marked with filled circles in Fig. 3. The wavelength of the dominate mode is extremely temperature stable, the wavelength temperature sensitivity is as low as 0.05 nm/°C, which is even lower than that caused by the refractive index change.[16] The lasing line blueshift resulting from the inhomogeneous nature of the QD ensemble, which

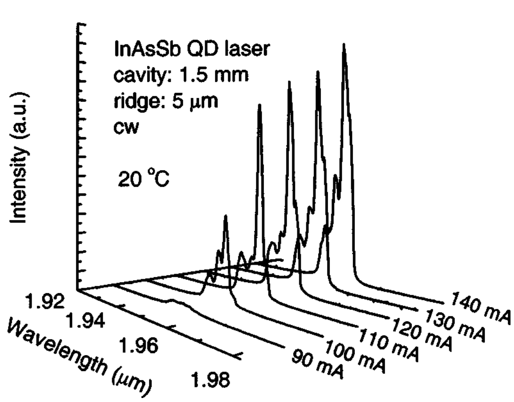

FIG. 2. Ground-state cw lasing spectra of a 1.5 mm cavity length laser measured at various currents at 20 °C.

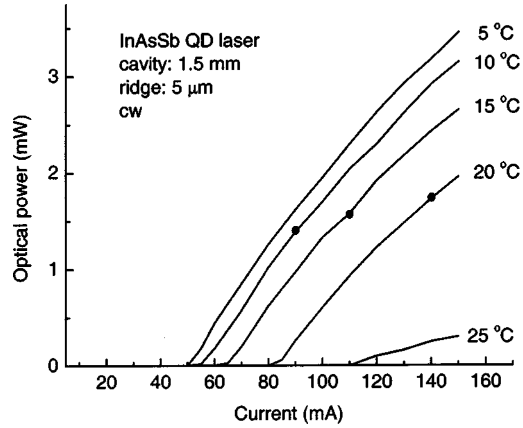

FIG. 3. Light vs current for a 1.5 mm cavity length laser without facet coating measured at different temperatures. The filled-circles mark the injection current at 1.6 I_{th} used to take spectra at Fig. 4.

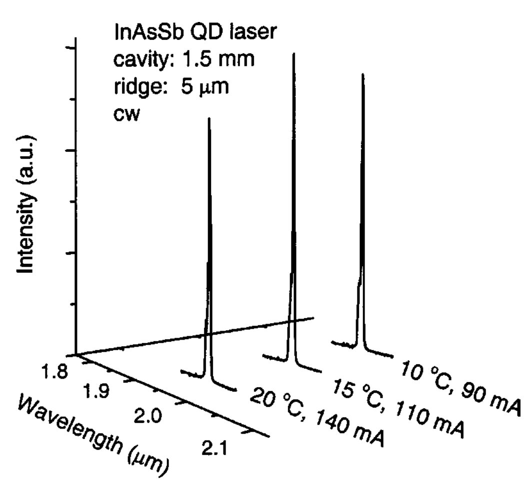

FIG. 4. Lasing spectra for a 1.5 mm cavity length laser at injection current of 1.6 I_{th} at three different temperatures, showing a wavelength temperature sensitivity of less than 0.05 nm/°C.

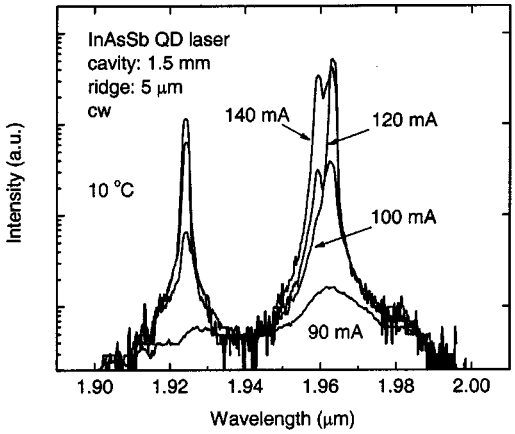

FIG. 5. cw lasing spectra of a 1.5 mm cavity length laser measured at various currents at 10 °C, indicating possibly lasing from ground state and excited state simultaneously.

compensates the redshift from the band gap shrinkage with increasing temperature, is dependent on the slope of the maximum modal gain function $G(E)$,[15] therefore it is not difficult to understand the extremely low temperature sensitivity.

Accompanied with higher threshold current, switching from the ground state to the excited state was observed on most lasers of 1 mm cavity length and some of 1.5 mm cavity length due to insufficient material gain from the single-stack QDs. An energy separation of 13–17 meV was determined for the excited and the ground states, which is very similar to that of InAs QD lasers on InP previously measured.[6] Figure 5 shows lasing spectra both from the ground state as well as the excited state at temperature of 10 °C. Further measurement in pulse operation will reveal clearly the phenomenon that the ground state saturates then the excited state dominates the spectrum at high injection current, since any current higher than 140 mA in cw operation would lead significant heating and low both lasing intensities.

In summary, we have reported the demonstration of room-temperature cw operation of single-stack InAsSb self-assembled QD lasers near 2 μm based on (001) InP substrate. The ridge lasers have a differential quantum efficiency of 13% and a maximum output optical power of 3 mW per facet with a threshold current density of 730 A/cm^2 at room temperature. A very low wavelength temperature sensitivity of 0.05 nm/°C is observed.

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